NASA Technical Memorandum 83506

Tensile and Compressive Constitutive Response of 316 Stainless Steel at Elevated Temperatures

(NASA-TM-83506) TENSILE AND COMPRESSIVE CONSTITUTIVE RESPONSE OF 316 STAINLESS STEEL AT ELEVATED TEMPERATURES (NASA) 26 p HC A03/MF A01 CSCL 11F

N84-15249

Unclas
G3/26 42605

S. S. Manson and U. Muralidharan
Case Western Reserve University
Cleveland, Ohio

and

G. R. Halford
Lewis Research Center
Cleveland, Ohio

Presented at the
Symposium on Nonlinear Constitutive Relations for High Temperature Applications
cosponsored by the University of Akron and NASA Lewis Research Center
Akron, Ohio, May 19–20, 1982

TENSILE AND COMPRESSIVE CONSTITUTIVE RESPONSE OF 316 STAINLESS STEEL AT ELEVATED TEMPERATURES

S. S. Manson and U. Muralidharan
Case Western Reserve University
Cleveland, Ohio

and

G. R. Halford
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

E-1851

SUMMARY

It is demonstrated that creep rate of 316 SS is lower by factors of 2 to 10 in compression than in tension if the microstructure is the same and tests are conducted at identical temperatures and equal but opposite stresses. Such behavior was observed for both monotonic creep and conditions involving cyclic creep. In the latter case creep rate in both tension and compression progressively increases from cycle to cycle, rendering questionable the possibility of expressing a time-stabilized constitutive relationship.

The difference in creep rates in tension and compression is considerably reduced if the tension specimen is first subjected to cycles of tensile creep (reversed by compressive plasticity), while the compression specimen is first subjected to cycles of compressive creep (reversed by tensile plasticity). In both cases, the test temperature is the same and the stresses are equal and opposite. Such reduction is a reflection of differences in microstructure of the specimens resulting from different prior mechanical history. If specimens of identical microstructure are tested in tension and in compression, large differences in creep rate are again evident, whether that microstructure was developed by prior loading in tensile creep/compressive plasticity or by tensile plasticity/compressive creep. The significance of the differences in creep rate under tension vs. compression, as related to the development of constitutive relationships for creep-fatigue problems, requires further study.

Little research has been conducted to explain the physical basis for this behavior. Several speculative reasons are offered, but require verification.

INTRODUCTION

It is common to assume that the creep characteristics of metals in compression are similar to those in tension. Such an assumption derives from the fact that the time-independent deformation characteristics in tension and compression are similar. Very few experimental programs, however, have been conducted to determine the validity of presupposing similarity of creep characteristics.

In the course of our studies of Strainrange Partitioning (SRP) over the past decade it has become clear to us that the differences between tensile and compressive creep rates at the same stress level can be appreciable, at least for 316 stainless steel, which we have investigated most extensively. The early tests in 1971 (ref. 1) on cyclic creep were very revealing in this respect. Loading was first in tension, allowing creep to develop a prespecified strain. The stress was then reversed to a compression of equal magnitude, and this stress was maintained until the compressive creep strain completely reversed the tensile strain. In many cases the time required to produce the compressive creep strain was as much as a factor of three or more higher than that to develop the tensile creep strain. This long time was, in fact, the basis for conducting what turned out to be the first cp test (in SRP terminology (ref. 2)) when an attempt was made to reduce the unacceptably long times required to reverse the tensile creep by imposing much higher compressive stress which reduced the reversal time essentially to zero. These tests (ref. 1) will be further discussed later in this report.

In addition to our experience with the cyclic creep tests, we have observed in a number of other test programs that the compressive creep rate at a given stress level is lower than the corresponding creep rate at an equal tensile stress. It is the purpose of this paper to outline the results of some of these experiments. Though the difference between tensile and compressive creep strain rates is not necessarily of great importance in many aspects of formulation of the constitutive relations discussed in this Conference, it may be of significance in some cases, as will be illustrated later.

The micromechanistic reasons for the differences in creep rates have not been extensively investigated; in this report we offer several speculations which, of course, require verification.

EXPERIMENTS INVOLVING DIFFERENCES BETWEEN TENSILE AND COMPRESSIVE CREEP RATES

The following discussion relates to observations wherein appreciable difference was observed between tension and compression creep rates. Although most of the results shown involve AISI 316 SS, we have also observed the effect in a limited number of other materials, which leads us to speculate the phenomenon is a general one, the magnitude of the effect varying, or course, among materials.

Cyclic Creep-Rupture Tests

Background. - Reference to these tests has already been made in the Introduction. They were initiated in an effort to improve the time-and cycle-fraction approach for treating creep fatigue, as discussed in reference 1. In this approach creep damage is taken as the ratio of time at which a given stress and temperature is imposed divided by the creep-rupture time at the same stress and temperature. Because the use of monotonic creep-rupture tests often gives poor results when so applied, and in recognition that creep-fatigue tests involved cyclic variations of stress, our hypothesis was that cyclic creep-rupture tests would produce improvements in predictions made by this method. Reference 1, in fact, demonstrates the validity of this hypothesis.

The type of test adopted for obtaining cyclic creep-rupture tests is shown schematically in figure 1. The loading was generally started in compression to insure that the stress level chosen would not immediately produce a runaway creep strain. As shown in figure 1 the selected stress was held constant until a specified total strain was reached, usually of the order of 1 to 2 percent. The time required is shown as AB in figure 1(a), and the strain pattern is shown by the curve OAB (fig. 1(b)). At point B the stress was reversed to tension, and this stress was held constant until a total tensile strain equal in magnitude to the compressive strain, was reached. The stress and strain patterns during this period are shown as BCD in figures 1(a) to (b), respectively. The pattern of reversal of equal stresses and strains in tension and compression was repeated successively as shown in figures 1(a) to (b) for as many cycles as were required to rupture. The hysteresis loop followed in all cycles was essentially OABCDA of figure 1(c).

The results of these tests are shown in figure 2, representing a plot of stress versus rupture time, as in conventional creep-rupture plots. Monotonic creep-rupture is shown by curve M. When only the tension time of the test is used (neglecting the reversal time in compression), the results are shown by curve N. In the analyses of reference 1 we found good agreement between predictions and experiments when several types of creep-fatigue tests were analyzed using the creep-rupture curve N in the "time-fraction" terms. The total time curve P, which includes the compression time, did not prove as useful as curve N in the analysis, and its experimental development required excessively long times.

As can be seen from figure 2, factors as high as five or more existed between P and N for times beyond 10 hours. In order to minimize the test time a type of loop as shown in figure 3 was developed. The compressive stress pattern BCE was introduced, reversing the creep strain AB by only essentially instantaneous plasticity. Thus the loop ABCDA (essentially what was later termed a cc loop in SRP terminology) was replaced by ABCEDA, later recognized as a cp loop (in the same terminology). While a small effect was produced on the tensile time creep-rupture curve N in figure 2, the curve so obtained for the cyclic creep-rupture representation of the material was equally accurate for creep-fatigue analysis by the time-and-cycle fraction method. Test time was, however, appreciably reduced.

Comparison of tension and compression creep rates. - Since the tensile and compressive stresses were of the same magnitude in the cc loops, and since the temperature was held constant, the results of these tests provide direct data for comparison of creep rates under the two loading conditions. Some of the data used are shown in figure 4 which is a scale plot analogous to the schematic of figures 1(a) to (b). Figure 4 shows two effects on creep rate. First, it is noted that both tension and compression creep rates vary as a function of time (or applied cycles). The time required to complete the first cycle is nearly a factor of 10 longer than the time required to complete the 90th cycle in this test which ran 98 cycles to cause rupture. In each cycle the time required to complete the tension creep is considerably shorter than the time required to complete the compressive creep of equal magnitude. Thus there are two major effects: the relation between the tensile and compressive creep rates in any single cycle, and the relations among the tensile and compressive creep rates in successive cycles.

The complete analysis of results shown in figure 4 is given in figure 5. Here both the tension and compression creep rates are plotted as a function of cycle ratio. It is clear from this figure that both the tensile and compressive creep rates increase as cycle ratio increases, varying by as much as a factor of 10 from the first cycle to the last few cycles. Similarly, it is clear that the tensile creep rate is greater than the compressive creep rate in each cycle. The compressive creep rate is, on average, about one-third the tensile creep rate.

An additional test which shows similar results is shown in figure 6. This figure also clarifies how creep rates were determined without introducing error associated with cross-sectional changes that are different in tension and compression. Figure 6(a) shows the hysteresis loop. By measuring the tensile creep rate at point E where the strain is zero, and the compressive creep rate at point F where the strain is also zero, true creep rates are determined, since the cross-sectional areas were exactly the same at the two points in the cycle. The creep rates are shown in figure 6(b). The tensile creep rate is again seen to be two to three times that for compression. Although the rapid increase in creep rate in the later cycles gives the illusion that the two curves are approaching each other, the difference by a factor of two to three persists until near-failure, as can be determined by measuring vertical distance between the two curves. Since the vertical scale is logarithmic, this constancy of vertical displacement implies a constant ratio between the two values.

Significance of results. - These results show not only that creep rate in tension differs from that in compression, but that both rates vary significantly during the lifetime, even for this simple repetitive loading pattern. Attempts to develop constitutive equations that will be applicable throughout the life should be in harmony with this simple observation.

On the other hand, it should be pointed out that stabilization has readily been achieved in SRP strain cycling tests involving creep in only one direction (ref. 1). Thus while some caution is required in seeking constitutive relations involving reversed creep, the more practical applications in which the major creep component occurs only in one half of the cycle (tension or compression) does not seem to involve this complication.

Constant Load Tests

Another series of tests we have conducted in which differences in tensile and compressive creep rates have been observed relate to ordinary static creep under constant load. The results are described below.

Specimen stabilization. - In these tests the specimens were first stabilized relative to cyclic plastic strain by the scheme shown in figure 7. The strain amplitude was first gradually increased to 1 percent while cycling at a frequency of 0.2 Hz. Then 30-40 cycles of the 1 percent strain amplitude were applied, after which the strain amplitude was reduced during cycling in a manner symmetrical to the forward-loading. The cycles at constant ±1 percent strain stabilized the material and established a repetitive hysteresis loop, similar to the manner a material is normally stabilized in room temperature fatigue to establish a cyclic stress-strain curve. Such curves do not

significantly reflect the hardening or softening characteristic of the early loading cycles. The stabilization was initially introduced because the intended purpose was to develop a constitutive creep model for the material for later use in creep-fatigue analysis. Thus it was thought appropriate to decouple the cyclic creep effects from the cyclic plasticity effects. In the present discussion we are concerned only with the static creep behavior of the stabilized material.

Figure 7(b) shows the hysteresis loops developed during the increasing amplitude straining (continuous lines), the stabilized hysteresis loop (heavy line), and the decreasing amplitude straining (dashed lines). It is clear that in the final state the net stress and strain are both zero. Thus the creep tests which follow are on specimens which have neither residual stress nor residual strain nor do they have a memory of prior straining in one particular direction. Since the stabilization cycling is very rapid (5 s/cycle), there is essentially no creep damage on the test specimens. Also, since the specimen can withstand about 15 such blocks as shown in figure 7(a), the amount of fatigue damage is also small.

Correction for cross-sectional area changes. - Typical creep curves obtained are shown in figure 8 which are for a nominal 123 MPa (18 ksi) stress in tension and compression at 705° C (1300° F). While the creep strain in tension (curve OAB) is clearly higher than that in compression, part of the difference is due to cross-sectional area changes rather than inherent differences in creep characteristics at the two stress states. In tension the cross-sectional area continuously decreases as the strain decreases. Thus, for the constant load (nominally 123 MPa (18 ksi) for the original cross-sectional area) the true tensile stress is continuously increasing. Likewise, the compression creep curve OA'B' involves an increasing cross-sectional area resulting in a continuously decreasing true compressive stress.

If we assume that creep rate at constant temperature is proportional to a power law of stress, m, we can correct the tensile creep rate at a strain, ϵ, by dividing by $(1 + \epsilon)^m$ to obtain the rate that would have been observed if the stress had been kept constant by reducing the load progressively. Similarly, for the compressive strain the creep rate must be divided by $(1 - \epsilon)^m$ to obtain the appropriate strain-independent creep rate.

Test results. - Figure 9 shows the results for tension and compression for a number of creep tests conducted at several stress levels in both tension and compression. Approximate straight lines can be drawn through the test results when steady state creep rate is plotted against stress on logarithmic scales. Thus a power law exists between the two variables. As seen in the figure, strain rate for both tension and compression vary as approximately the 11th power of stress, the multipliers being different depending on whether the loading is tension or compression, and whether the cross-sectional area correction is applied or not. However, even when the correction is applied, the creep rate in tension is about a factor of 5 greater than in compression. The "engineering" values, for which no correction is made, show differences of about a factor of seven.

Significance of results. - These results show that, at least for 316 SS at 705° C (1300° F), it is inappropriate to develop constitutive relations based on the assumption that tensile creep rate and compressive creep rate are

equal at the same stress and temperature. However, they also show that creep rate varies as the 11th power of stress. Thus, to maintain a creep rate in compression equal to that in tension it is necessary to increase the compressive stress by only a small amount. If, for example, the creep rate at a tensile stress of 276 MPa (40 ksi) is to be reproduced as an equal value under compression, the compressive stress need only be increased to 317 MPa (46.40 ksi). When tests are conducted which are strain-controlled, forcing equal tensile and compressive creep rates will cause the compressive stress to be higher than the tensile stress (16 percent in the present illustration).

No reversed creep was involved in these tests. How the results would be affected by the presence of such creep requires further study. But from the results of Section A it is speculated that a significant effect could develop. Constitutive relationships for application to cyclic creep and plasticity might require appropriate recognition of this phenomenon.

Thermomechanical Loading Tests

Applications involving simultaneous variation in stress, strain, and temperature, commonly called thermomechanical loading, are among the most important cases for which constitutive modeling is required. Because a cooperative program between Case Western Reserve University and NASA Lewis is currently underway, it is appropriate to include here some of the results which are pertinent to the question of the relation between tensile and compressive creep characteristics.

Tests in progress. - Figure 10 shows some of the control patterns of tests that are in progress. These tests use AISI 316 SS specimens, not, however, stabilized according to the pattern of figure 7. In one type of test, figure 10(a), the strain and temperature are cycled in-phase, high temperature and tensile stress being achieved simultaneously. Such a loading usually develops cp type of strain because the highest tensile stresses occur while the temperature is high, causing creep, while the highest compressive stresses occur when the temperature is low so that no compressive creep occurs. In the second type of loading the strain and temperature are out-of-phase, producing net compressive creep because the temperature is high only when stress is compressive.

Creep rates during actual cycling. - Ideally, it would be desirable to compare the creep rates of the specimens at the same temperatures and at equal but opposite stresses at appropriate points in the in-phase and out-of-phase cycling where such conditions develop. Unfortunately, such conditions do not develop for the very reason that compressive creep response differs from the tensile creep response. This fact can be seen in figure 11 which shows the stresses developed as a function of temperature during the in-phase and out-of-phase tests. If tensile and compressive creep response were similar, the two curves would be mirror images of each other with respect to the horizontal axis. The fact that the compressive stresses reached are larger than the tensile values, verifies that creep rates at a given stress and temperature are lower in compression than in tension. Thus, to maintain the equal strain rates imposed, a slightly higher stress develops during the out-of-phase loading tests, as is clear from figure 11. From this figure it can be seen, then, that it is not possible to compare directly specimens taken from each of these tests when they are at the same temperature and at stresses which are equal in magnitude but of opposite sign.

By writing analytical relations for creep rates in the two tests in terms of stress and temperature, it is possible, however, to calculate the creep rates at the same stress in tension and compression. Several forms of constitutive relationships have been studied; we consider here only the simplest type taken in the form of the Arhenius equation

$$\dot{\epsilon} = A\sigma^{m} \exp(-\Delta H/RT) \tag{1}$$

where

$\dot{\epsilon}$	creep rate
σ	stress
T	temperature
A, m, ΔH, R	constants

Analyses were made using the in-phase data only, the out-of-phase data only, and combining all the data into one correlation. A complete discussion of all the results will be published when the program is completed; the tentative results pertinent to the current subject will be discussed only briefly.

Using the common formulation of all the data, including both the in-phase and out-of-phase results, equation (1) becomes:

$$\dot{\epsilon}_{ss} = 124\ \sigma^{10} \exp(-181\ 000/T) \tag{2}$$

where

σ	stress, ksi
T	temperature, °R
$\dot{\epsilon}_{ss}$	steady state creep rate per second

Figure 12 shows the correlation between the experimental creep rates measured in both the in-phase and out-of-phase tests and the computations based on equation (2). The agreement is quite good, suggesting a common constitutive relationship for both tension and compression creep rates as a function of stress and temperature. While this result is very satisfying from the analyst's view of desiring to neglect differences between tensile and compressive constitutive behavior, it seems to negate the findings about the differences discussed. In order to clarify the apparent discrepancy, additional tests were conducted as discussed in the next section.

<u>Creep rates at approximately constant microstructure.</u> - The microstructure of a specimen sampled at a point of tension during the in-phase loading can be considerably different from the microstructure of a specimen sampled from an out-of-phase test at the same temperature (and approximately equal but opposite stress). Thus, although it is fortuitous that the same equation can be used to determine the strain rate vs. stress relations of both specimens, the equality of tensile and compressive creep rates does not negate our general finding that the compressive creep rate is lower than the tensile creep rate at the same temperature and equal both opposite stress. To determine if this finding is general, and still valid for material in thermomechanical loading, it is necessary to conduct tests in tension and compression of material in the same microstructural state. Ideally, a scheme such as shown in figure 13(a) would be suitable for this purpose. The hysteresis loop represents the path, for

example, of in-phase loading. At point A the thermomechanical loading is discontinued, and temperature and stress are "frozen" and maintained constant at the value achieved at this point. By holding the stress constant creep strain occurs along AB as a function of time as shown in Inset I of figure 13(a). The steady state creep rate which develops is then characteristic of the tensile creep behavior of the material in its microstructural condition at A. To obtain the compressive creep characteristic we should, ideally, use a second specimen, stabilize the loading loop by applying the same number of cycles, stop again at point A, and then reverse the stress to an equal but opposite value, maintaining the temperature. The path A'B', both on the stress-strain diagram, and the strain-time diagram of Insert II then represents the compressive characteristic of the material in its microstructure of point A'. The creep curves of Inserts I and II provide the needed comparison of tension and compression for a material in the same microstructural condition.

The scheme actually used in this program is shown in figure 13(b). A single specimen was first crept along AB, after which the load was reversed to an equal but opposite value, and the compressive creep characteristic A'B' was obtained. This procedure was used for two reasons: conservation of specimens, and avoiding the possibility of scatter resulting from using separate specimens. Actually, then, a small change in microstructure was introduced by the tensile creep AB for the material subsequently tested along A'B'. However, the economy and efficiency of using a single specimen was deemed sufficient to justify the alternate approach in the preliminary tests. Furthermore, our expectation was that the compressive creep rate would be lower than the tensile creep rate. Since it is reasonable to assume that the prior tensile creep AB would, if it had any effect, accelerate the compressive creep rate (in accordance with the results of figs. 1 to 3), any observed lower creep rate in compression would in fact be accentuated were the prior tensile creep not imposed.

A number of tests of the type described above were conducted, stopping at various points in the in-phase loading loop. Similarly, analogous tests were conducted by stopping at selected points of compressive stress in the out-of-phase loading, and conducting tests in both compression and tension for microstructures developed in these tests. Typical results shown in figure 14(a) relate to one of the tests for in-phase loading; figure 14(b) displays results for out-of-phase loading. It is clear that in both cases the creep rates in compression are significantly lower than those in tension. The other tests corroborated these observations.

We can conclude from this study that the generality holds for material in thermomechanical tests, namely that if material is sampled from any point in its path and tested both in tension and in compression, the tensile creep rate will be considerably higher than the compressive creep rate. The two tests must, however, be conducted on material in the same microstructural state.

Cyclic Loading of Hastelloy X

It is interesting to study the results of Walker (ref. 3) on Hastelloy-X to ascertain whether the general behavior observed on 316 SS also applies to his material. Some of his test results are shown in figure 15.

Walker's tests were conducted on a specimen which was continuously cycled at a constant strain rate, stopping at various points to establish the creep rate for the material in its current metallurgical state. After each creep loading at constant stress, the loop was re-stabilized before proceeding to the next point. Thus the creep tests were on materials in different metallurgical states, and direct comparison of tension and compression involves the difficulties already discussed in connection with figure 12. However, it is still instructive to make the comparison because the careful experiments do reveal differences in the two creep rates.

The continuous curves of this figure show experimental creep curves at various stresses. Some are tension creep curves, others compression. While the comparison can be made by direct examination of the curves of figure 15, the cross-plots of figures 16 and 17 are more convenient for quantitative comparison.

Figure 16 shows the cross-plot of stress versus strain after 40 seconds. OA shows the strain developed after this time for tensile loading and OB the strain for compression loading, for each of the stress levels studied. The dotted curve OB' is a replot of OB, changing signs of both stress and strain. By comparing OA to OB' it is clear that at any stress level the amount of strain in tension is more than that in compression after the 40 seconds used as a parameter. The cross-plot of figure 17 shows the ratio of strain developed in tension to that developed in compression after various times for the 147 MPa (21.5 ksi) tests. While these results are not as dramatic as those we have obtained for 316 SS, it is quite clear that tensile creep rate is higher than compressive creep rate at the same temperature and equal magnitudes of stress.

PARAMETERS THAT CAN AFFECT CREEP RATE AS A FUNCTION OF STRESS DIRECTION

The reason for the differences in creep rate at equal tensile and compressive stress has not received much attention. In fact, the phenomenon is not sufficiently well recognized to have stimulated study. We can only speculate at this time why the phenomenon exists. Following are some possibilities:

Effective Friction at the Grain Boundary

One way of viewing the problem is by analogy to friction of masses in contact moving relative to each other. Since creep frequently involves grains sliding along their boundaries we can regard the individual grain motion and the "friction" between them. The treatment is complicated, of course, by the fact that there are numerous grains oriented at numerous directions relative to each other. A simplified analysis is shown in figure 18 which assumes an average orientation of 45°. Drawing the analogy with the movement of a weight on a frictional surface, shown in figure 18(a), we can see in figure 18(b) that the net frictional force is larger when two grains are in compression than when they are in tension. If we consider the ratio, R, of the creep rate in tension to the creep rate in compression to be a power function (power, m) of the ratio of the respective normal stress, σ_n, we obtain the results shown in figure 18(c). The plot shows the relationship for different choices

of μ (coefficient of friction) and m. It is seen that reasonable choices of μ and m produce R values agreeing with our experimental results.

Change of Lattice Parameter

The average size of the lattice increases in tension and decreases in compression. An effect can thus be produced on diffusionally controlled creep rate. According to the explanation given in reference 5, close-packed crystals like fcc and hcp have a partial molar volume of vacancies that is an appreciable fraction of the molar volume of the metal. Under a hydrostatic component of stress in compression the specimen will lose vacancies in an effort to relieve the pressure. This decrease in the concentration of vacancies will in turn decrease the self diffusion.

If creep rate is influenced by self-diffusion, as is commonly accepted, a component of hydrostatic compression should reduce creep rates and hydrostatic tension should increase creep rates.

Grain Boundary Cavitation

At high temperature, cavities are generated in the grain boundaries which are in tension, facilitating the movement of one atom over the other, thus increasing creep rates. In compression, however, the cavities are absent or collapsed even if activated previously in tension. This phenomenon is shown schematically in figure 19. Accordingly we can expect higher grain boundary creep when the net force across the grain boundaries is tensile than when it is compressive.

Defects Other Than Grain Boundary Cavitation

Any defects developed in the microstructure of the material would tend to be open in tension and closed in compression (fig. 20). Hence there would be greater tendency for reduction of cross sectional area experienced by local stresses in tension. Therefore, the creep rate would be higher in tension than in compression.

CONCLUDING REMARKS

In all of the various types of tests that we have studied, tensile creep rate has always been higher than compressive creep rate if the loading is on specimens that have the same microstructure. This similarity of microstructure may be the result of absence of significant prior straining history, or it may be the result of a complex history of thermomechanical loading. Differences in creep rates from 2 to 10 have been observed. However, if the microstructure of the specimen in tension is different from that in compression, the general pattern of behavior can be altered, although in the limited cases we have examined, there is still a bias toward lower creep rate in compression. Some of the effect is geometrical - tension producing a higher true stress because of decreases in cross-sectional area, while the area of a compression specimen increases. However, even when appropriate corrections are made for cross-

sectional variations, the qualitative comparisons are not altered, although quantitatively the effect is somewhat smaller.

Of special interest is the observation that during in-phase and out-of-phase thermomechanical loading, the microstructures that developed - although assuredly different - were such that creep rates in tension and compression tended to be the same. Whether there is a natural tendency for microstructure to develop to produce such a lack of bias remains to be determined by studying additional loading patterns and other alloys. From an engineering point of view, this effect is fortuitous because it makes more accurate the assumption usually made that the two creep rates are equal.

Even when there is an appreciable difference between the two creep rates at equal but opposite stresses, the error of engineering calculations based on the assumption of rate equality is mitigated by the fact that creep rate bears a high-exponent (on the order of 10 or 11) power law relationship to stress, so that only moderate changes in stress are needed to bring the actual creep rates to equality. Also, it is fortunate that in most of the important engineering problems involving stress and strain reversal, particularly thermal fatigue problems, the loadings are governed by imposed strains and strain rates. Thus the assumption that the stresses developed follow the same stress/strain/strain-rate relationships in both tension and compression produces only small error in the stress determinations. Were the loads specified, the errors in stress and strain rates would be much higher.

Thus, while the effect of the phenomenon is somewhat suppressed in some practical engineering problems, its presence cannot be negated. As illustrated in this report at least some applications can better be understood in terms of the characteristic differences between creep rates in tension and compression. Further experience may reveal other important applications. In any case it is an interesting phenomenon, both from mechanistic and analytical viewpoints, and it merits recognition and further study.

Finally, this study has led to a closer focus on a long-held observation that a combination of tensile and compressive creep produces an anomalous effect, at least on 316 SS. When creep is either absent or monotonic - i.e. in pp, pc, or cp loading, we have usually found that after a few cycles of loading a stable hysteresis loop develops. Stress and strain become repetitive with respect to time as measured from some arbitrary point on the hysteresis loop. When reversed creep is present, i.e. involving cc loading, the temporal aspects of the loop are not repetitive. In the cases we have studied, extreme softening takes place, and an attempt to apply a single constitutive relationship to characterize all cycles could lead to significant error. The mechanistic effect here, as well as the mechanisms that cause creep rate in tension to be much higher than that in compression, justify further study. Such study should lead to an improved understanding of the nature of creep in engineering materials and provide a useful input toward determination of appropriate time-dependent constitutive relations for handling reversed creep.

REFERENCES

1. Manson, S. S.; Halford, G. R.; and Spera, D. A.: The Role of Creep in High Temperature Low Cycle Fatigue. Advances in Creep Design; The A. E. Johnson Memorial Volume, A. I. Smith and A. M. Nicolson, eds., Applied Science Publishers, 1971, pp. 229-249.

2. Manson, S. S.; Halford, G. R.; and Hirschberg, M. H.: Creep-Fatigue Analysis by Strain-Range Partitioning. Symposium Design for Elevated Temperature Environment, S. Y. Zamrik, ed., American Society of Mechanical Engineers, 1971, pp. 12-24.

3. Walker, Kevin P.: Research and Development Program for Nonlinear Structural Modeling with Advanced Time-Temperature Dependent Constitutive Relationships, Final Report. (PWA-5700-50, United Technologies Research Center; NASA Contract NAS3-22055.) NASA CR-165533, 1981.

4. Manson, S. S.: Some Useful Concepts for the Designer in Treating Cumulative Fatigue Damage at Elevated Temperatures, Mechanical Behaviour of Materials; Proceedings of the Third International Conference, K. J. Miller and R. F. Smith, eds., Pergamon Press, 1980, vol. I, pp. 13-45.

5. Shewmon, Paul G.: Diffusion in Solids. McGraw-Hill, 1963.

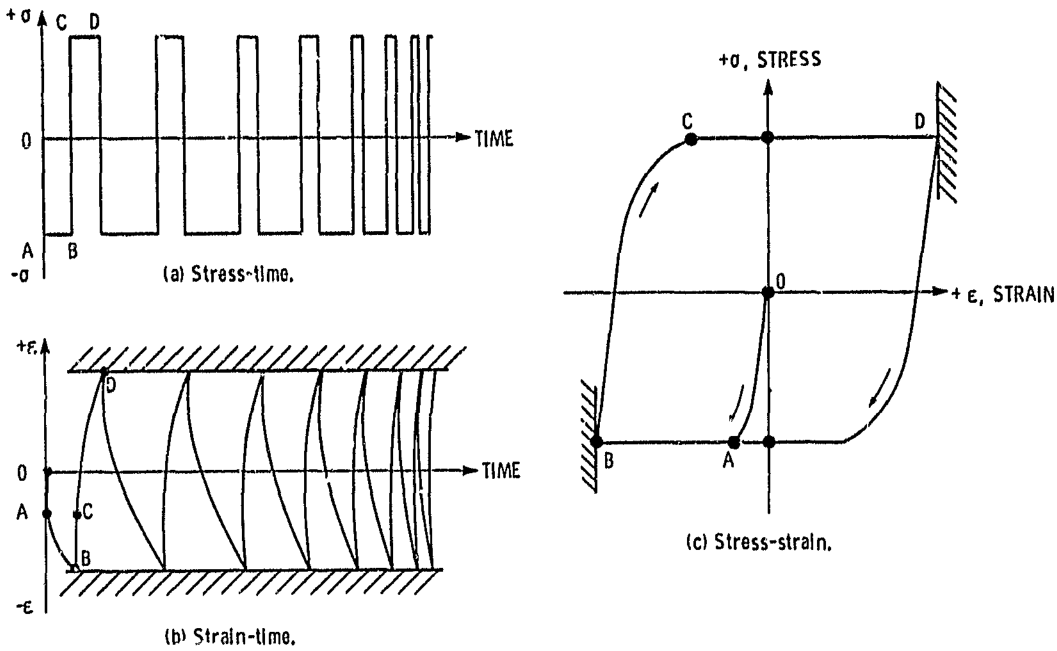


Figure 1. - Schematic diagram of the cyclic creep experiment.

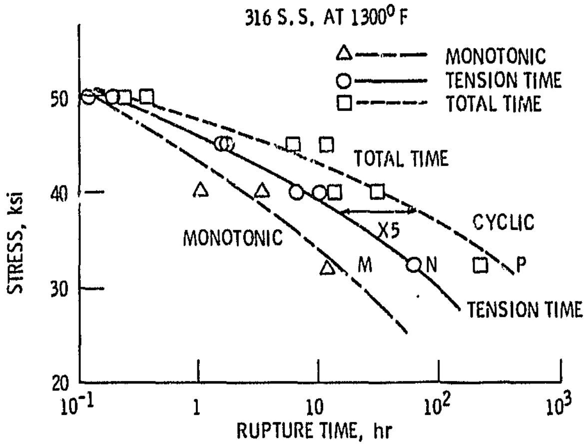


Figure 2. - Tension time and total time to rupture from the cyclic creep-rupture tests and time to rupture under monotonic creep plotted as a function of stress (Ref. 1).

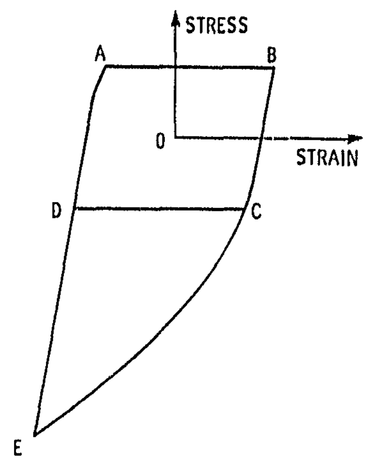


Figure 3. - Schematic diagram of "cc" loop ABCDA, creep in tension reversed by the creep in compression, and "cp" loop ABCEDA, creep in tension reversed by the plasticity in compression.

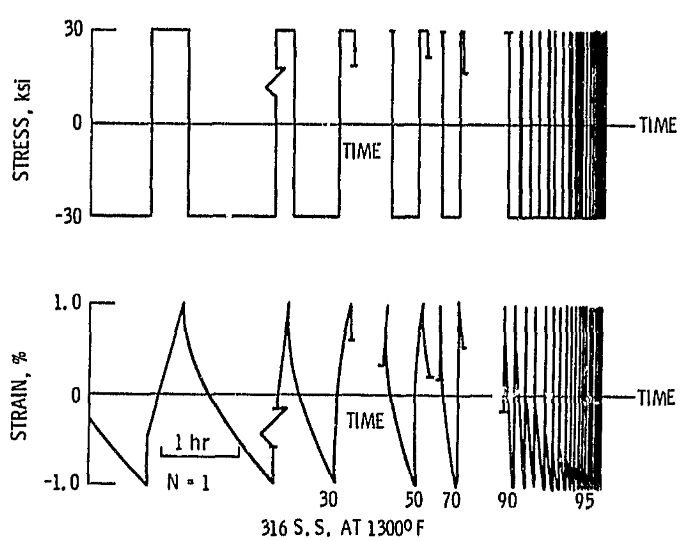


Figure 4. - Stress and strain response of a typical cyclic creep-rupture test conducted on AISI 316 stainless steel at 1300° F.

ORIGINAL PAGE IS
OF POOR QUALITY

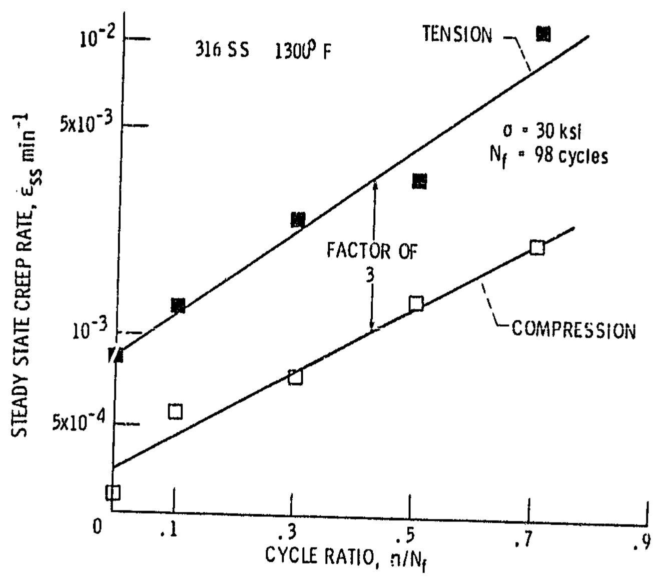


Figure 5. - Tensile and compressive creep rates as a function of applied cycles for the cyclic creep-rupture test shown in figure 4.

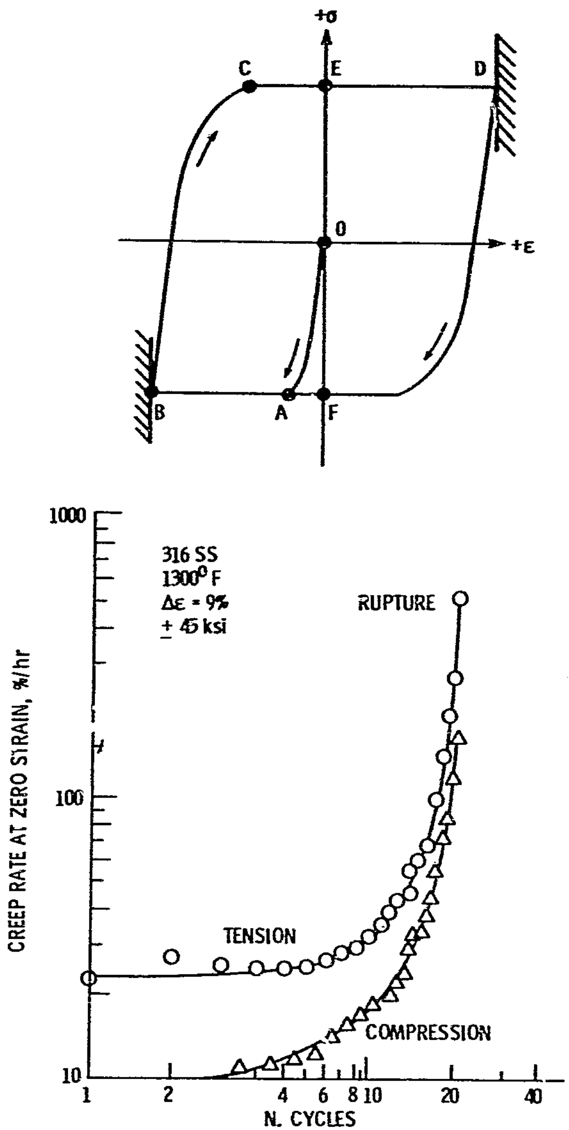


Figure 6. - Tensile and compressive creep rates measured at points of zero strain (E and F) plotted as a function of applied cycles for a cyclic creep-rupture test.

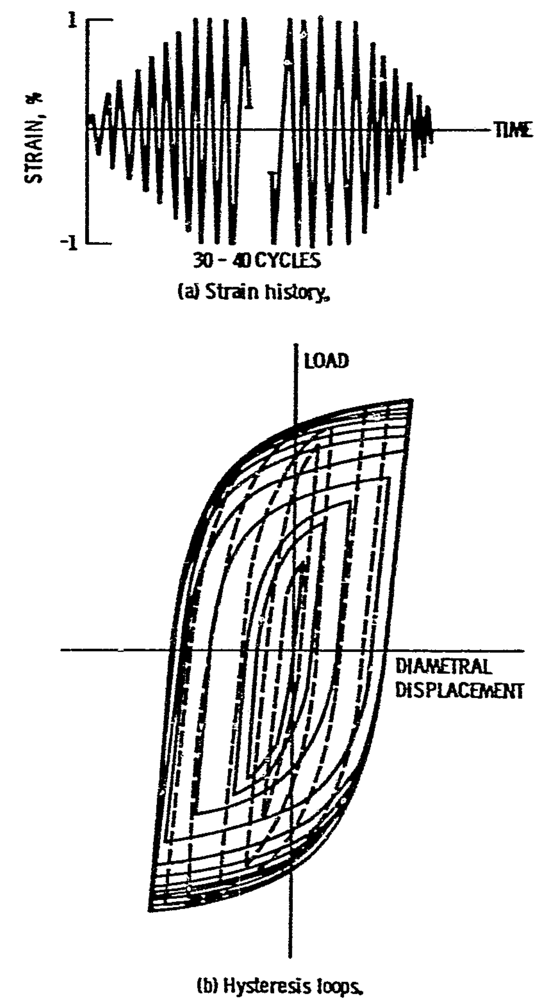


Figure 7. - Stabilization of AISI 316 stainless steel at 1300° F by rapid strain cycling at 0.2 Hz.

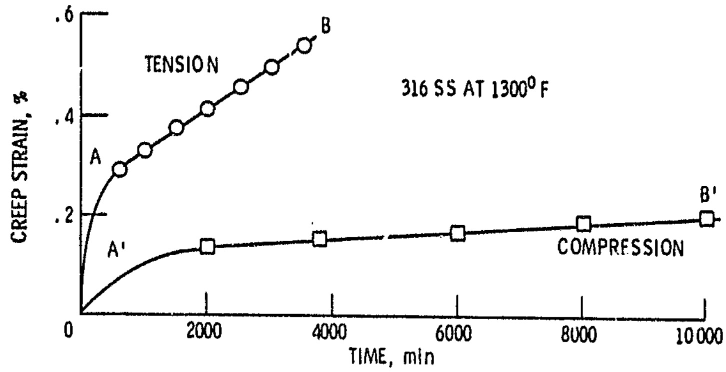


Figure 8. - Creep responses in tension and compression for typical tests conducted at ± 18 ksi.

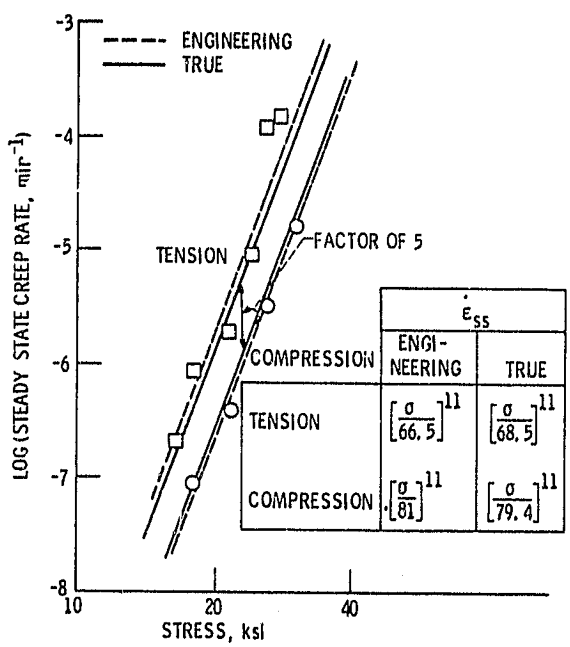


Figure 9. - Engineering (observed) and true (corrected for the change in cross-sectional area) creep rates plotted as a function of applied stress on log-log coordinates.

ORIGINAL PAGE IS
OF POOR QUALITY

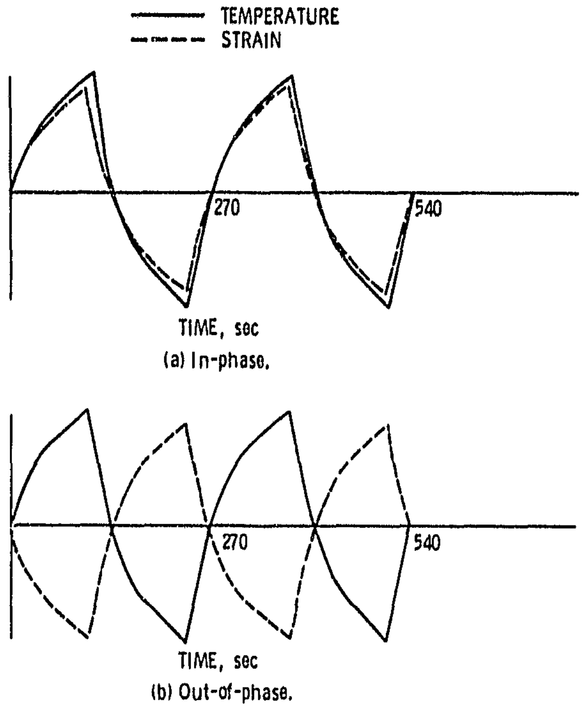


Figure 10. - Temperature and strain variations with respect to time in in-phase and out-of-phase thermomechanical tests.

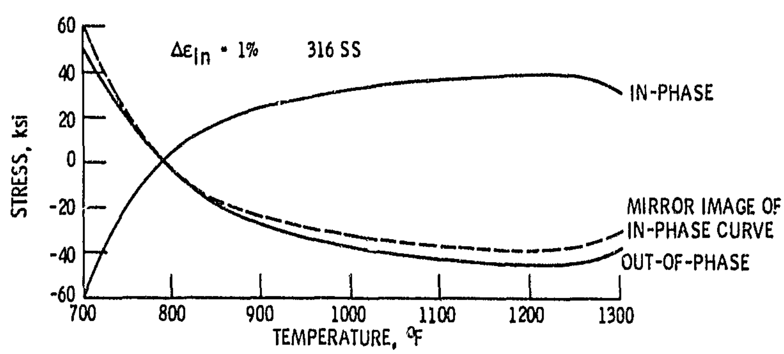


Figure 11. - Stress-temperature responses for the in-phase and out-of-phase tests.

ORIGINAL PAGE IS
OF POOR QUALITY

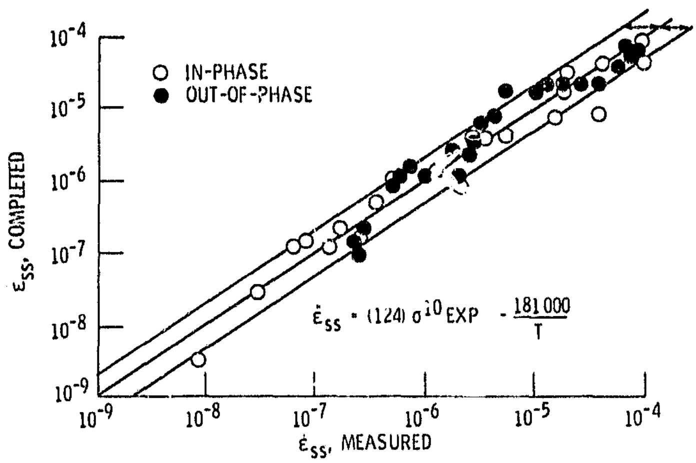
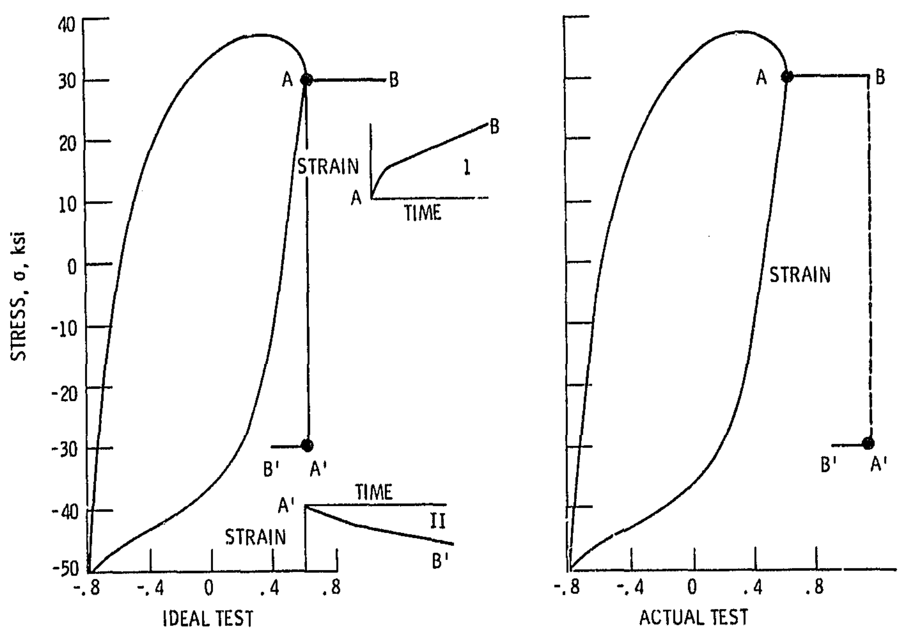


Figure 12. - Comparison of the measured steady state creep rates with the rates computed by the formula given above, 316 stainless steel.



(a) Tension and compression at identical microstructure.

(b) Small microstructural change introduced in compression by prior creep in tension.

Figure 13. - Stress-strain response of a typical in-phase thermomechanical test.

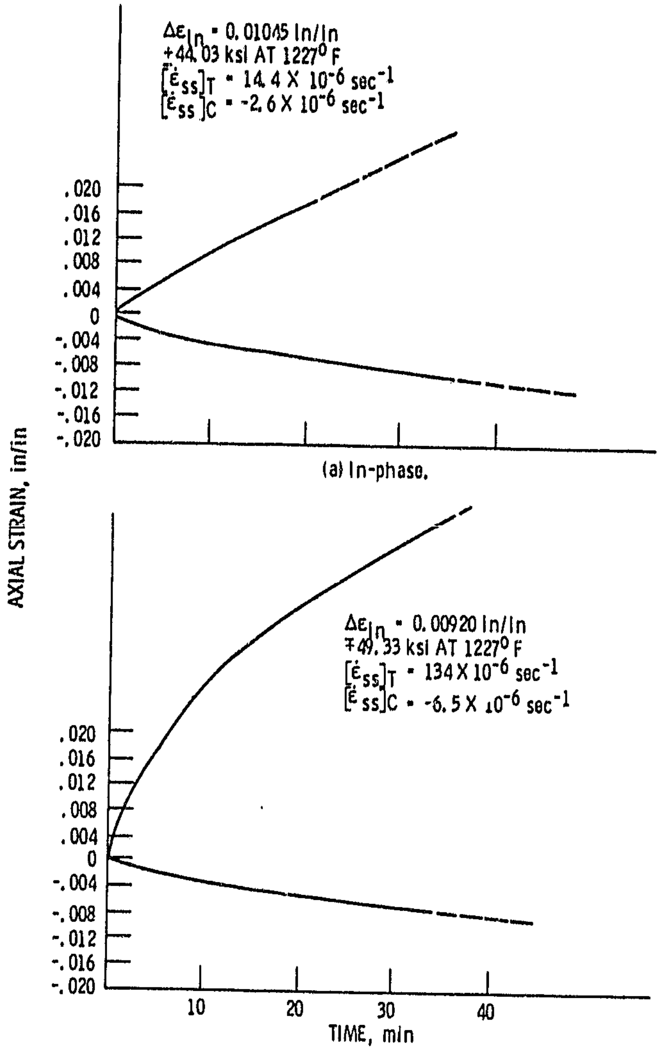


Figure 14. - Creep responses in tension and compression at the stress levels shown for the in-phase and out-of-phase thermo-mechanical tests on 316 stainless steel.

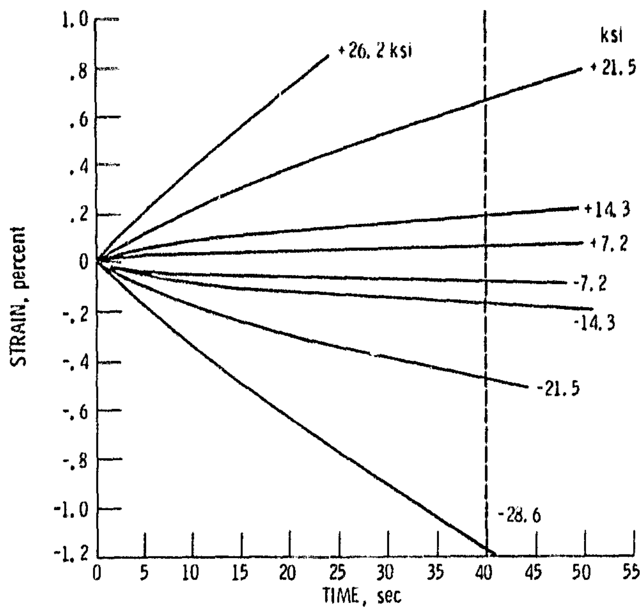


Figure 15. - Creep responses in tension and compression of Hastelloy-X at 1600° F for stress levels shown (Ref. 3).

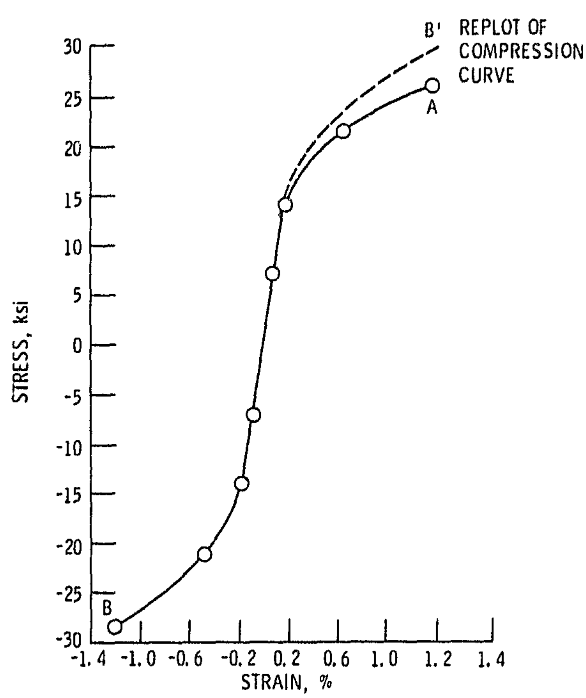


Figure 16. - Creep strains plotted as a function of stress at a given time of 40 sec, Hastelloy X, 1600° F.

ORIGINAL PAGE IS
OF POOR QUALITY

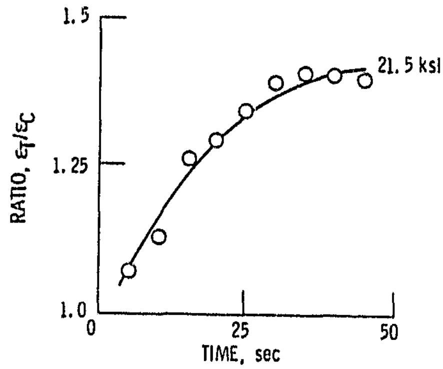


Figure 17. - Variation of the ratio of tensile to compressive creep strains shown as a function of time, Hastelloy X, 1600° F.

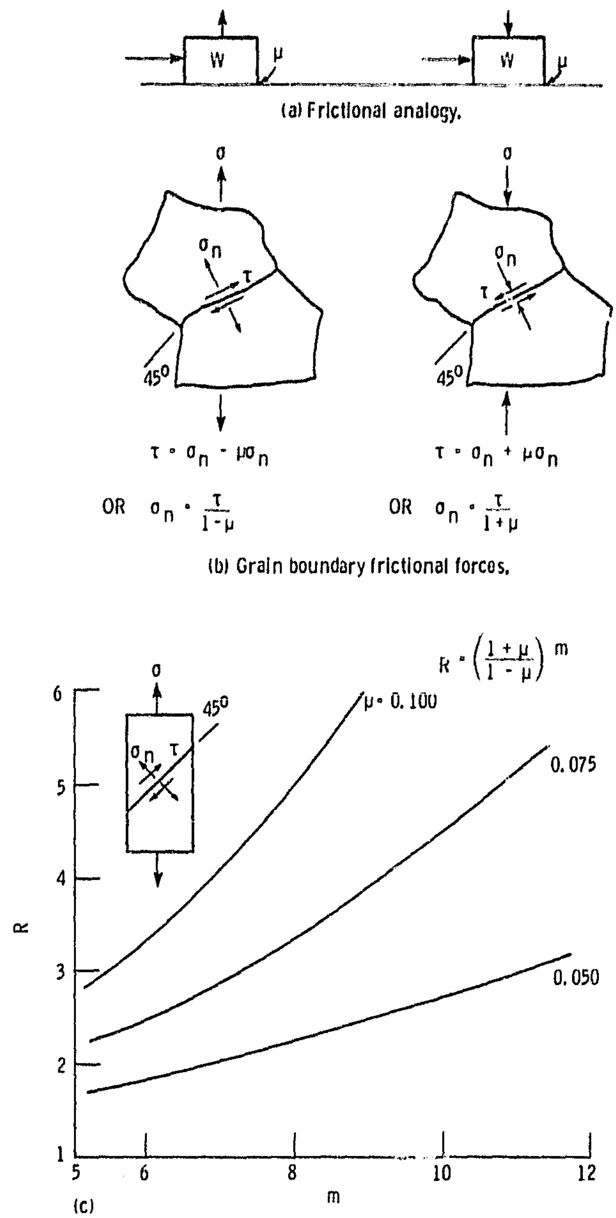


Figure 18. - Ratio of the creep rates in tension to that in compression due to effective friction at the grain boundary shown as a function of exponent 'm'.